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A Review on Applications of Model Predictive Control to Wind Turbines

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***Abstract*—This paper aims to give an overview of the recent development and benefits of model predictive control in wind turbines and its future potential. For a modern large wind turbine, the main objective of control is to maximise the power production while maintaining the fatigue loads to be minimal. With such multiple objectives, a multivariable system and actuators constraints the popular PI controller may become ineffective or hard to tune whereas MPC provides a systematic approach for designing a multivariable controller incorporating the knowledge of actuator constraints. This paper reviews the wind turbine control problem and in particular gives a survey of the use of model predictive control on wind turbines.**

***Index Terms*—model predictive control, wind turbine**

I. INTRODUCTION

Wind energy is one of the most promising and fast-growing renewable energy resources in the world. A horizontal-axis wind turbine (HWAT) is a complex and non-linear dynamic system. Nowadays, wind turbines are becoming larger with bigger rotors in order to make wind energy more cost effective compared to oil and gas. Hence, control technologies play an important role. There is a vast amount of literature covering control in wind turbines and they can be classified into three categories: operational control, power electronics control in wind energy and supervisory level control. This review paper will focus mainly on the operational control. The main objective of the operational control is in general to maximise the captured power by the wind turbine while minimising the loads on the turbine components such as blades, tower and drive train. Many sensors and actuators are already installed in this giant and flexible system. Therefore, the potential benefits of using advanced control design in wind turbines are well motivated.

In the past decade, control techniques such LQG and H_∞ have been prevalent in the literature. However, there is no clear sign that either of these techniques have been adopted by industry. One of the possible reasons could be that LQG and H_∞ controller design cannot incorporate the system and input constraints in a systematic fashion. Those controllers often require high level of input activities and violating constraints will cause the undesired shutdown of wind turbine. Therefore, model-based predictive control (MPC) in wind energy applications has become popular in academic community recently due to its intrinsic capacity for dealing with multivariable systems and constraints. Consequently, the main aim of this paper is to give a general overview and survey of the recent development of MPC within wind energy applications; this in turn will indicate areas where future work is needed.

This paper is organised in four sections. Section II and III provide readers problem description on wind turbine control and motivation of using MPC in wind turbine control respectively. This is followed by an overview of existing literature on MPC wind turbine control in Section IV. Lastly, a conclusion and future directions will be given in Section V.

II. PROBLEM DESCRIPTION OF WIND TURBINE CONTROL

A. Control Objectives

The operation of a standard variable speed wind turbine is based on the wind speed and can be divided into main four regions of operation as shown in Figure 1. In Region I, the wind speeds below the cut-in speed v_{min} are too low to drive the wind turbine. In Region II, the wind turbine will maximise the captured wind power below the rated wind speed v_{rated}. Region II operation also named as partial load region. In Region III (also known as full load region), the wind turbine is only allowed to operate at the rated power P_{rated} due to the limitation of power equipment rating. Above the cut-out speed v_{max} in Region IV, the wind turbine stops operating to prevent mechanical damage.

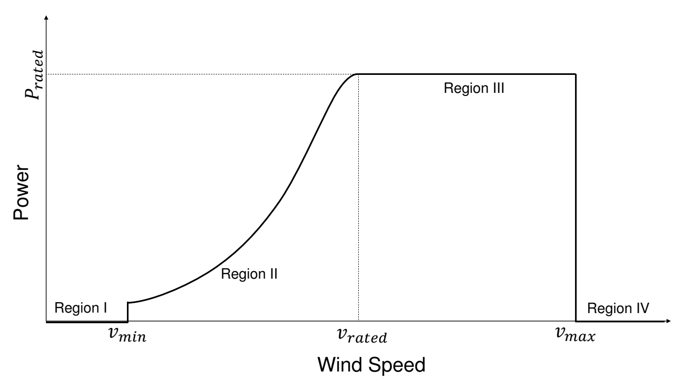

Fig. 1. Power Curve of A Standard Wind Turbine [1], [2]

The control objective can be categorised in two main themes as shown in Table I; rotor speed regulation and structural load mitigation. There are more control objectives for wind turbines such as fault-tolerant control. Due to the limitation of this paper, the author will mainly focus on operational control.

TABLE I
SUMMARY OF MODERN WIND TURBINE CONTROL OBJECTIVE

Control Objectives	Control Variables	Measured Variables
1) Rotor Speed Reguation		
Track the optimum tip-speed ratio to maximise the power production in Region II	Generator torque demand	Generator speed
Regulate the rotational speed to produce the rated power in Region III	Collective pitch demand	Generator speed
2) Structural Load Mitigation		
Minimise tower fore-aft loads	Collective pitch demand	Tower fore-aft acceleration
Minimise tower side-side loads	Generator torque demand	Tower side-side acceleration
Minimise rotor, drive-train, blade loads	Individual pitch demand increments	Blade root loads

The objectives on operational control strategy are based on the operational region. In the past, the wind turbine control objectives in the industry focus on rotor speed regulation with a PI design. Many papers suggest that MIMO control and advanced control strategies can improve the wind turbine speed regulation performance and load mitigation [3], [4], [5].

B. Model Description

Many methods to construct wind turbine models have been studied by the control community for the purpose of designing controllers to achieve the control objectives. The National Renewable Energy Laboratory (NREL) designed an aeroelastic model of a three-bladed variable-speed wind turbine with 16 degrees of freedom [6]. Nevertheless, in many publications, a reduced nonlinear wind turbine model with just three degrees of freedom has been used for model-based control design. The reason behind this is that a reduced model requires less computational power to simulate and the reduced model is good enough to fulfil most of the design criteria. A model comparison is available in [7]. Table II summarises a list of control and measured variables used in literature and their possible corresponding constraints. The actuator limits and system constraints vary between turbines; in this paper, the author provides only the general range of limits used in various literature [8], [9], [2].

The reduced nonlinear wind turbine model usually is described by two dynamics. The common assumptions made to the turbine model are: (i) no yaw misalignment; (ii) rigid blade; (iii) first mode of tower fore-aft deflections and (iv) uniform wind or no wind shear. The dynamics of the rotor are

$$J_r\dot{\omega} = M_a(\beta, \omega, v) - M_g \tag{1}$$

where the aerodynamic torque M_a is a nonlinear function of blade pitch angle β, rotor speed ω and wind speed v. J_r and M_g are the moment of inertia of the rotor and generator torque respectively. The tower fore-aft deflection x_t is modeled by the following dynamics:

$$M_t\ddot{x}_t + D_t\dot{x}_t + C_t x_t = F_t(\beta, \omega, v) \tag{2}$$

where the thrust F_t is also a nonlinear function. M_t, D_t and C_t are the mass of turbine, damping coefficient and spring constant respectively.

Some other dynamics such as side-side tower motion, pitch servo model and blade model for individual pitch control will be also considered during the controller design. More details about wind turbine modelling can be found in [10], [11].

III. MOTIVATION OF MPC TO ADDRESS WIND TURBINE CONTROL PROBLEM

A wind turbine is a multi-variable system. Consequently a model-based control design approach is a suitable tool because it can build a controller to tackle the multi-variable control problem in a systematic fashion. It is not surprising therefore that the application of model predictive control (MPC) in wind energy applications has become more prevalent in the last 5 years. Much of the literature (e.g. [12], [13] and [14]) demonstrated that using a MPC approach to design a controller can lead to a better load mitigation and optimal power tracking than using a PI design approach; this is pertinent as PI is still widely used in the industry. Some publications [15] suggest that MPC controllers, due to their effective use of information about system constraints and predicted behaviour, can avoid unnecessary shutdowns due to overspeed limits. Other publications [4] and [16] suggest that MPC controllers improve upon the performance of alternative advanced control techniques such LQR and LQG; again this will be largely due to the effective handling of constraint information.

The main benefits of implementing MPC are: [17]

- An MPC algorithm can take systematic account of actuator constraints, as the constraints can easily be integrated into the optimisation of the cost function.
- MPC allows a systematic design procedure for handling multivariable control problems.

An MPC design approach consists of the following main components: Model, Performance Index and Constraints, although there is quite a bit of flexibility within the definition of each component to allow for the context.

A. Modelling choices

The control trajectory prediction and performance of a MPC controller is dependent on how the model is formulated which in turn depends upon the context and availability of data. Due to the nonlinearity of the wind turbine reduced model, in [18] and [12], a MPC controller is built by using a linearised model based on a single operating point; this will of course have limited applicability. Another common approach (e.g. [19]

TABLE II
CONTROL AND MEASURED VARIABLES OF WIND TURBINE

Control Variables	Constraints
Pitch Actuator $\beta, \dot{\beta}$	-2°to 30°, ±10°/s
Generator Torque τ_e	20% of the rated value
Trailing Edge Flap	-
Measured Variable	**Maximum Limits**
Generator Speed ω_e	10% of the rated value
Tower Fore-aft Acceleration	-
Tower Side-Side Acceleration	-
Blade Root Blending Moment	-
LIDAR Wind Measurement	-
Pitot Tube Wind Flow Measurement	-

and [20]) is to exploit the idea of gain-scheduling or Linear Parametric Varying (LPV) control to design a controller and thus to have different models and controllers for numerous operating points. Non-linear MPC (NMPC) is also a popular design method [7] which fits the nature of non-linearity of the wind turbine operational problems, but identifying and using nonlinear models is a much more challeging than determining local linear approximations.

Effective prediction depends on good information about future disturbances and inputs and consequently there is a lot of focus on estimating future wind profiles. In the literature there are different methods used in estimating the wind information. Typically, inversion of static aerodynamic model [12], [21] and random walk model[4] are common choices for wind estimation. Recently, with the increased maturity of the LIDAR technology, some papers obtain the estimated future wind information via LIDAR [7], [15].

B. *Objective function*

Within MPC control laws, the predicted input trajectory is obtained by optimising an objective function online. In most wind turbine control literature, the control objectives are mainly to improve the load mitigation and optimal power tracking. For the purpose of comparison of controller performance, it is common to study the power fluctuation and extreme loads of each component during a sudden gust and also the fatigue loads over a period of time. The fatigue loads are represented by the Damage Equivalent Loads (DEL) which is widely used in the industry.

C. *Constraints*

Constraints handling is the major feature of MPC relative to other control techniques. In wind turbines, there are often constraints such as pitch rate limits, pitch actuator limits and also desirable limits on the loads. The knowledge of these constraints can be incorporated into the objective function and thus the predicted control input trajectory should be optimal, subject to the system limitations. A list of system constraints is summarised in Table II.

IV. ANALYSIS AND ISSUES ON MPC APPLICATIONS TO WIND TURBINES

In the existing literature, many MPC applications have been used to address wind turbine control problems. In this section, an overview of some of existing literature will be covered.

A. *MPC and Rotor Speed Control*

Power production is the key to a wind turbine. In order to ensure the turbine is operating at optimum power efficiency, rotor speed control plays a vital role. In industry, this control objective is usually done by a simple PID controller. Many papers suggest that using a MIMO MPC approach can achieve not only better rotor speed but also tower loads mitigation.

1) Linear MPC: Unsurprisingly, one of the most common approaches adopted by researchers is to design a MPC controller based on a linearised wind turbine model to track and regulate the power production. The major argument is that the associated MPC algorithm for a linearised model requires less computational power (and indeed programming demands) than a nonlinear model.

Korber and King [12] demonstrate that a MPC controller based on a linearised model can achieve good performance on power regulation and tower loads mitigation in Region III. Another example, Henriksen [18], shows that a linear MPC controller designed on a single operating point should be able to handle the entire range of wind turbine operation, as long as the underlying design is made to be robust; readers may recognise that different tuning choices, filtering and set computations will affect the underlying robustness of a MPC control law [22].

2) Scheduled MPC: Some publications take the premise that a controller based on one single operating point might not have good performance over a wide range of operating regions. Kumar et. al. [20] point out that due to nonlinearity of the wind turbine, designing a MPC controller based on multiple models at different wind speed operating points is needed.

Soliman et. al. [14] demonstrate a scheduled MPC controller can achieve significant load mitigation and good power tracking throughout the whole operating region. Another important finding is observer-based controllers (e.g. scheduled MPC) offer the bumpless switching property. This is significant as bumpless transfer has not been straightforward with a scheduled PI controller changing its gains, especially during the transition between Region II and Region III [2]. The main control variable in Region II is generator torque whereas in Region III it is blade pitch. As the power tracking objective depends on the operational region, a sudden wind gust around the rated wind speed will cause a torque overshoot in Region II and large pitch activity in Region III. The problem can be avoided by using a scheduled MPC controller with its prediction capacity.

3) Nonlinear MPC: The major reason why nonlinear MPC (NMPC) in wind energy applications is worth substantial investigation is because of the highly nonlinear nature of the wind turbine operational control problems. Of course the counter argument is the higher computational burden (and coding complexity) required to solve the associated optimisation problem.

Bottasso et. al. [4] design a NMPC controller with collective blade pitch and generator torque as control inputs and they compared the NMPC controller with scheduled LQR and wind-scheduled PID controllers. The hub wind speed model is built based on random walk model. In their results, a normalised cost function against different operating wind speed is given. Also, a performance comparison during a sudden wind gust in Region III is provided. It is concluded that the NMPC controller can significantly improve the regulation of the rotor speed variation compared with scheduled PID and LQR controllers.

Some papers [23] argue that there is no significant improvement in load mitigation when using NMPC as opposed to scheduled MPC over the entire range of operations. They show that the NMPC controller has similar performance compared to the scheduled MPC controller on the pitch activity, rotor speed and fatigue tower loads but using NMPC increases the computational effort.

To sum up, MPC design approaches showed a promising performance on load reduction and power tracking. Furthermore, since MPC requires the solution of an online optimisation, the relatively low computational demands of linear MPC makes this a logical design choice as compared to nonlinear MPC. There has been little careful consideration of how the vast literature on robust linear MPC (e.g. [24], [25]) can be used effectively for wind energy applications. It is unsurprising therefore that there is a good motivation to put more effort into studying and improving the MPC implementations in this area.

B. MPC and Feedforward in Wind Turbines

With the recent development of LIDAR technology, wind turbine manufacturers are interested to mount LIDAR on the wind turbine to estimate the upstream wind speed. In a classical wind turbine controller, wind speed fluctuation is considered as a disturbance. But with feedforward control, the disturbance is incorporated into the control action. It leads the less pitch activity and better rotor speed and tower motion regulation. Thus several publications have begun to look at the LIDAR feedforward (FF) MPC in wind energy applications.

Implementation of MPC with FF control is a challenging problem [26]. Rossiter and Valencia-Palomo demonstrate that if a FF controller is designed without regard for the value of the input horizon, then one might get significantly suboptimal performance. Furthermore, if the set point trajectory is assumed to be time varying beyond the control horizon, the *optimal* feedback law will never reach a steady state value and thus is sub-optimal. Several papers [27] and [7] demonstrate the benefits of using LIDAR feedforward technology on a wind turbine. The FF control design approach is based on the assumption of constant future wind. This design approach might lead to a sub-optimal solution. However, even with a sub-optimal MPC solution, the literature still indicates improvements in power tracking and load mitigation can be achieved by using LIDAR MPC.

Koerber and King [15] suggest that in MPC, feedforward control can be easily integrated into a feedback controller via system inversion. Schlipf et. al. [7] construct a NMPC for the entire operating range and FF controller pitch demand is obtained by system inversion. Both papers make comparison between FF MPC and FF PI. Although both feedforward controllers are done via system inversion, the sub-optimal results still show better performance on rotor speed regulation, pitch activity and tower loads reduction.

The above mentioned studies uses the future wind information as a constant average and use the feedforward information in a relatively simplistic way, which means the feedforward control design might be sub-optimal. For the future work, more systematic guidelines on the design and implementation of MPC with a FF design should be developed.

C. MPC and Offshore Floating Wind Turbine

In recent years, researchers began to study the potential of advanced controllers for addressing the control problems occurring in floating wind turbines. Compared with a fixed wind turbines on land, an offshore floating wind turbine encounters extra dynamics from the floating platform; these dynamics are significantly slower than the natural frequency of the tower motion. Due to the two time scale nature of this system implementing a classical PI pitch controller on the wind turbine will often cause instability [29]. This problem is known as negative damping.

Schlipf et. al. [28] suggested that MPC is a good candidate to solve the floating wind turbine control problem. The MPC design approach can easily handle multivarible problem, incorporate the preview of wind and wave disturbances obtained by LIDAR and also it can well cope with the state constraints. Their results demonstrate a NMPC with collective blade pitch and generator torque inputs can solve the stability problem as well as achieve significant reduction in tower extreme loads and rotor speed deviation. In the paper, an assumption is made that there is perfect wave and wind information.

Lackner [29] suggests a novel load mitigation method for floating turbines by making the rotor speed set point in Region III varying with the motion of the platform. In this applications, there is potential of using MPC to ensure no constraints are violated and time-varying set point tracking.

To sum up, MPC is a suitable tool to address the floating wind turbine negative damping problems. In the future work, the paper suggests the need for a MPC with non-perfect wind and wave information. Also, since the blade loads only reduce slightly, future investigations can look at the possible applications of individual pitch control on floating wind turbine to reduce these loads further still.

TABLE III
SUMMARY OF BENEFITS AND FUTURE POTENTIAL OF MPC APPLICATIONS IN WIND TURBINES

Benefits of MPC in Wind Turbine
Performance on optimal power tracking and load mitigation on tower has improved significantly compared with PI controller
Bumpless switching solution for transition between Region II and Region III
Avoidance of overspeed of the rotor and negative damping of floating turbine tower motion
Future Potential of MPC in Wind Turbine
Generator torque as control input often is assumed to be an ideal actuator
More careful integration and tailoring for wind energy of the literature on robust MPC as an alternative to NMPC.
Study with more realistic wind information and wind shear is encouraged, especially in individual pitch control
In MPC feedforward design, disturbance should be incorporated into the prediction model rather than a system inversion method
Non-perfect wind and wave information can be included in the floating wind turbine study
Fault-Tolerant control can include more fault scenarios such as LIDAR sensor and distributed actuators

D. MPC and Individual Pitch Control

Modern wind turbines have been increasing in size and rotor diameter in recent year. Individual pitch control (IPC) design becomes popular due to its capacity to mitigate the loads on rotor, blade and drive train by adjusting the blade pitch angle individually. These loads usually appear at the harmonics of wind turbine rotational speed. It is a common practice to decouple the IPC controller loop from the speed control collective pitch controller loop [30]. In IPC, pitch activity increases heavily hence MPC is a fitting tool to ensure smooth pitch activity due to its capacity of prediction and constraints handling.

Mirazei et. al. [31] demonstrate the feasibility of using MPC on a mulit-blade coordinate transform IPC controller and also show that MPC is an effective tool to deal with this multivariable constrained control problem. In that work, a collective pitch controller and IPC controller are implemented. The objective of the IPC controller is to reduce the root blade bending moment by varying the pitch angle based on the measured wind speed. The reference value for pitch against the wind speed is calculated when the flapwise bending moment deviation is zero. The results show the IPC controller has a better mitigation on blade loads reduction compared to a PI IPC controller.

Friis et. al. [32] use a model taking into accounts of the non-uniformity of the wind speed across the rotor. Each individual pitch command is calculated by solving a MPC problem with measured disturbances. The prediction horizon is taken as the time distance between two blades. The result shows a MPC IPC controller can improve the loads mitigation on the drive train, tower and blade relative to an industry standard PID controller.

MPC Applications in IPC has demonstrated the ability to reduce the rotating blade loads, fixed rotor loads and drive train loads. However, the installation difficulty of blade root strain gauge is a concern. A paper [33] suggests blade bending measurement can be estimated from fixed structure instead of rotating blade. The other concern is the inaccuracies in measurement, model and prediction will lead to erroneous pitch angle trajectories. Also, there is no clear consideration yet in the literature of the computational burdens induced by IPC.

E. MPC and Trailing Edge Flap Control

Trailing Edge flap control aims to improve aeroelastic stability of the blades by adjusting the trailing edge flaps (TEF) which are installed along the blade. Lackner and van Kuik [34] suggest that TEF control can achieve similar flapwise blade loads reduction with much less pitch activity than IPC. This result becomes more useful when more wind turbines are installed in remote areas or offshore as the chance of wear and tear of the pitch actuators should be kept to a minimum over the 20 years lifespan of wind turbines.

The idea of TEF control is relatively new. There are only a few publications on MPC applications on individual flap control. Castaignet et. al. [35] suggest that the ability of handling the actuator constraints makes MPC a suitable candidate for solving individual flap control and the paper demonstrates a MPC TEF controller can achieve flapwise blade fatigue loads reduction. Recently, the paper [36] showed that a demonstrator turbine with MPC TEF controller was tested and the performance agrees with the proposed improvement.

MPC on TEF control shows a promising flap wise blade load reduction. MPC on TEF control is a new concept and further conclusions can be made only when more research becomes available.

F. MPC and Fault-Tolerant Control in Wind Turbine

Fault-Tolerant control in wind turbine is to ensure when faults occur in turbine components or unexpected scenarios happen, the fault have minimal influence to the turbine operation, hence, to minimize the downtime of wind turbines. MPC is a good candidate for fault-tolerant controllers with its capacity of constraints handling.

Yang et. al. [37] demonstrate the MPC implementation on a fault-tolerant controller. The paper studies faults occurred at pitch system and sensors. The comparison has been made to compare the default controller to fault tolerant MPC. Koerber and King [15] study the case of grid loss and show that MPC with knowledge of state constraints can minimise the tower motion during sudden grid loss.

To summarise this section, there are three main benefits of using MPC in wind turbine control:

- MPC design can handle MIMO wind turbine control problems systematically, especially useful for floating turbine, IPC and TEF control.
- Constraints handling allow MPC to reduce the excessive pitch activity and the chances of overspeed of the rotor
- Feedforward control action can be easily and systematically incorporated into MPC if the measured disturbance are included into the prediction model; this could be especially useful for turbine with LIDAR.

V. Conclusion and Future Directions

The wind turbine controller design is a challenging task. The controller requires not only to have good optimum power tracking capacity and tower stability, but also to perform good components loads mitigation and faults detection and compensation. In this paper, we have examined the use of model-based predictive control design approaches in wind energy applications to address the control challenges. The main advantages of model predictive controller in wind turbines are the capacity of handling constraints such as pitch rate and rotor speed and the systematic design for handling the MIMO wind turbine control problem. Table III gives the reader a summary of advantages of using MPC design approach in wind turbine control and also identifies areas where future research is likely to be of most benefit.

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